Temperature Processor

Channel	ID Code	Description
320	LMT2M	Local met temperature 2.4 m
322	LMT24M	Local met temperature 24.48 m (data1-data7)
322	LMDT	Local met Δ temperature, 24.48 m - 2.4 m (data8-Phase IV)
324	LMDP2M	Local met dewpoint 2.4 m

Location	Met rack in data shed
Range	-50°C to 50°C (ambient and dew point) -8°F to 12°F (delta)
Resolution	20 °C / Volt (ambient and dew point) 2.22°C / Volt (delta)
Calibration method	Manufacturer specifications (M5) and electronic path calibration (E1)
Output level	0-5 Vdc
Accuracy	maximum error of ±0.1°C over specified processor operating temperature
Description	Platinum RTD processor (range specified by customer) Met One Instruments Model: 49.03A (rack mount), 21.32/21.43 (processor), 48.11B (power supply)

Amplifier calibration voltage calculation

1. Manufacturer calibration of RTD sensor yields values for R_o and α. Customer data sheet accompanying processor contains values for R_2 (LO) and R_3 (HI).
2. The values for EHI and ELO are determined for a specific sensor/processor pair using the following formulae:

$$TCAL = \frac{A - (A^2 - B)^{0.5}}{1.1751E-6}$$

$$A = \alpha + 0.000058755$$

$$B = 2.3502E-6\frac{R - R_o}{R_o}$$

where, R is R_2 for determination of ELO and R_3 for determination of EHI.

3. The voltage is then determined using the following formula:

$$ECAL = 5\frac{TC - TLO}{THI - TLO}$$

where THI and TLO describe the temperature range specified when ordering the processor. TC = TCAL for absolute temperature modules. For delta temperature modules, both modules are calibrated separately, and the voltage is determined using TC = TCAL2 - TCAL1 where TCAL2 represents the delta temperature module and TCAL1 represents the absolute temperature module. When calibrating dew point temperature modules, if THI and TLO represent dew point temperatures, the TCAL value must be converted to dew point using the following formula:

$$DPCAL = 0.68434 * TCAL - 23.88 .$$

Then the voltage is determined using TC = DPCAL, THI = DPHI, and TLO = DPLO.

Here are typical values not corrected for variations in processor and sensor. This results in a probable error of ±0.1°C and a worst case error of ±0.3°C for the temperature and dew point measurements. For delta temperature, the error is doubled. It is recommended that the corrections specific to processor and sensor be used to restrict the error to ±0.05°C. These typical values were used to calibrate the processors for Phase III and Phase IV data collection because the manufacturer supplied parameters were unavailable.

Temperature	EHI = 4.819V, ELO = 2.500V
Delta T	EHI = 4.338V, ELO = 2.000V
Dew point	EHI = 4.445V, ELO = 1.306V

Calibration Procedures

Manufacturer specifications - (M5)

1. The RTD sensors and the dew point sensor were calibrated by Met One Instruments before installation.
2. Using the calibration voltages determined above, the temperature processors are adjusted as follows:
   a. For each processor set the mode switch to LO, and adjust voltage to ELO ± 2 mV. Set the mode switch to HI, and adjust voltage to EHI ± 2 mV.
   b. For the delta temperature processor offset, set the mode switch of the delta temperature processor and of the ambient temperature processor to LO. Determine the ΔT offset using the TC values from step 3. Compute the ΔT offset output for this ΔT offset temperature.

$$Voffout = 5\left(\frac{\Delta Toffset - \Delta TLO}{\Delta THI - \Delta TLO}\right)$$

   Adjust the zero voltage to the calculated offset voltage.

   c. Set mode switch to OP for normal operation.
3. Enter the slopes (20°C/V for ambient temperature and dew point, 2.222222°C/V for delta temperature) and offsets (2.5°C for ambient temperature and dew point, 2°C for delta temperature) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the temperature channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and insure that the correct PCM stream is specified in *gencal.cap* (all meteorological channels are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts respectively.

Calibration frequency

The RTD sensors were calibrated by the manufacturer prior to Phase III data collection. Amplifier adjustment, offset determination, and electronics path calibrations were performed prior to each series of data collection which lasted less than 2 months.

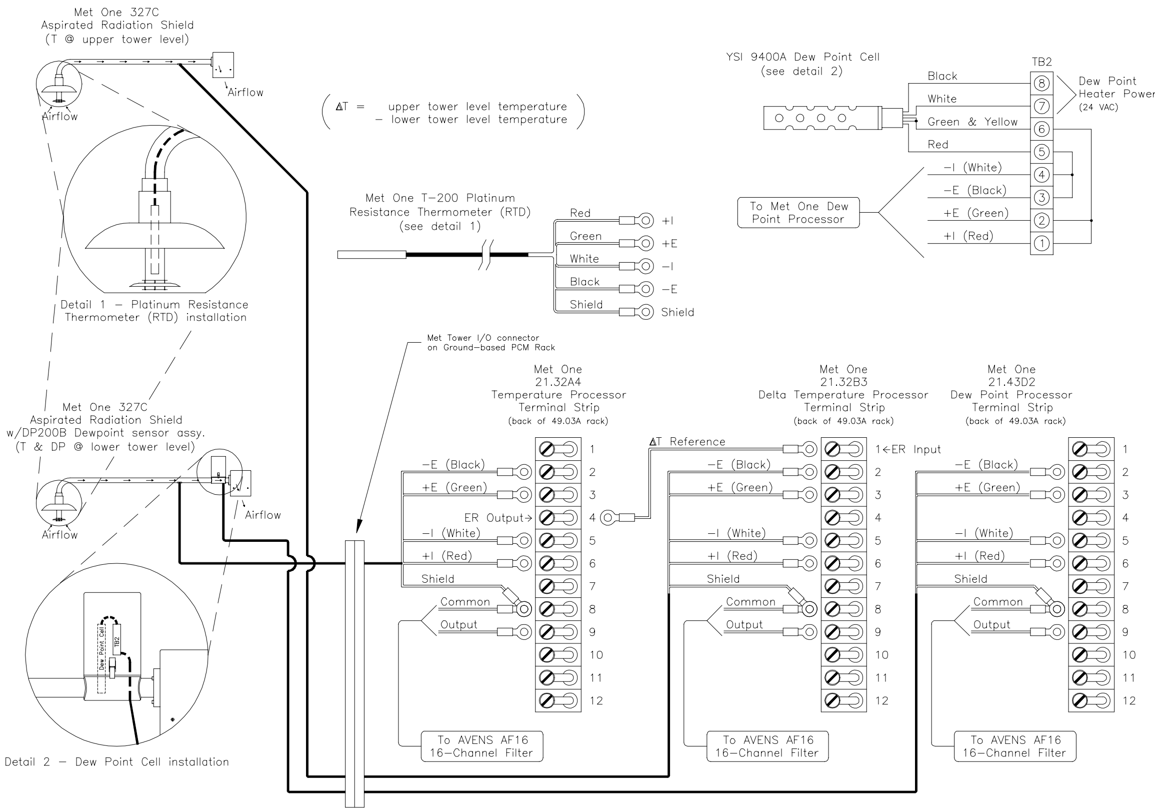
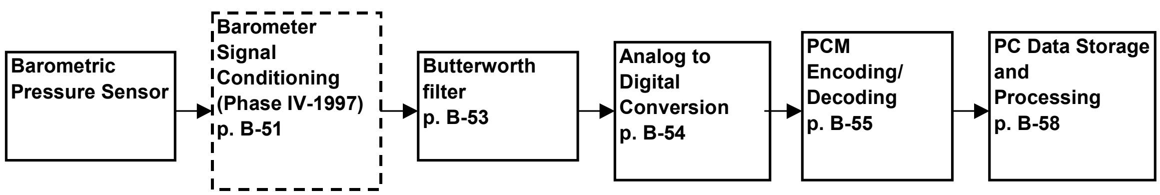


Figure B.4. Temperature, delta temperature, and dew point wiring diagram.

Channel	ID Code	Description
334	BARO	Barometric pressure

Location	Met rack inside data shed
Measurement type and units	Ambient air pressure, Pa
Excitation	15 Vdc
Range	74000 to 100000 Pa = 0 to 5V
Resolution	5200 Pa/V
Calibration method	Manufacturer specifications (M6) and electronic path calibration (E1)
Sensor description	Ambient air pressure transducer Atmospheric Instrumentation Research, Inc. Model: AIR-AB-2AX



Note: The barometer that was used for Phase III data sets data1-data6, parked1, parked2, slwrot2, and slwrot3 was calibrated with a maximum value of 80,000 Pa. Thus, the instrument's maximum input was exceeded during these data campaigns.

Calibration Procedure

Manufacturer specifications - (M6)

1. A calibration was performed by Atmospheric Instrumentation Research before installation of either barometer.
2. Enter the nominal slope (5200 Pa/V) and the nominal offset (74000 Pa) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the barometer channel is listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and insure that the correct PCM stream is specified in *gencal.cap* (all meteorological channels were on stream 3).
2. Connect the precision voltage generator to the barometer output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V respectively. These values are stored in a temporary header file,

.hdr. These slope and offset values are combined with the manufacturer provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts respectively.

Calibration frequency

The barometers were calibrated by the manufacturer prior to each phase of data collection. The electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.

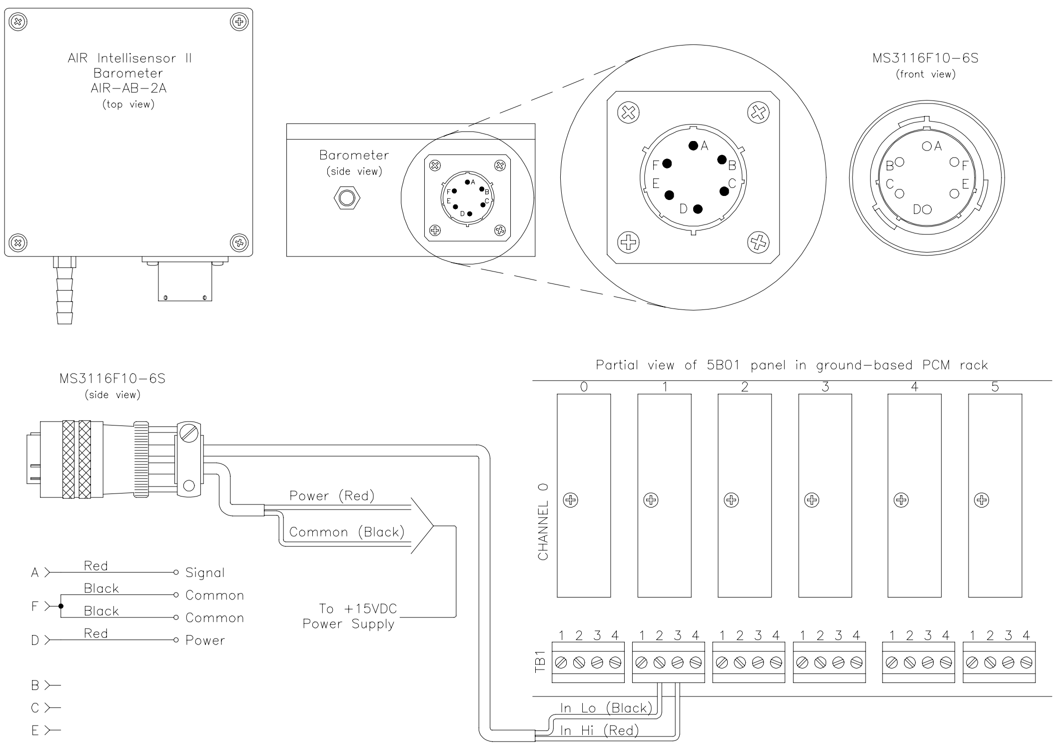
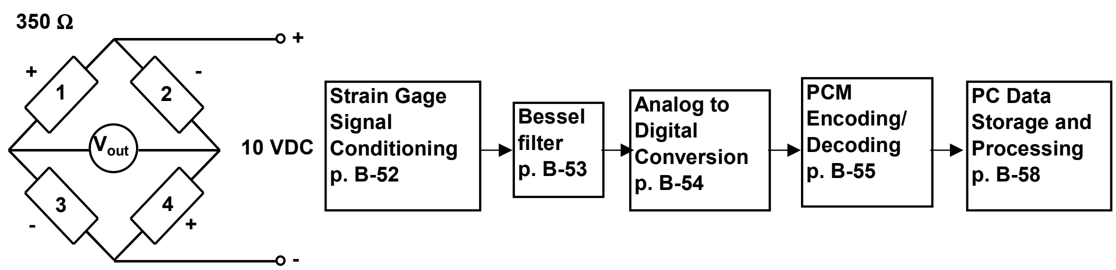


Figure B.5. Barometer wiring diagram.

Strain Gages (Root)

Channel	ID Code	Description
225	B1RFB	Blade 1 root flap bending moment
227	B1REB	Blade 1 root edge bending moment
229	B2RFB	Blade 2 root flap bending moment
231	B2REB	Blade 2 root edge bending moment
233	B3RFB	Blade 3 root flap bending moment
235	B3REB	Blade 3 root edge bending moment

Location	Pitch shaft (8.6% span), 8360 Steel
Measurement type and units	Bending moment, Nm
Excitation	5Vdc
Range	± 5000με
Resolution	2000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: LWK-09-W250B-350



Note:

1. Flap bending is positive in downwind direction; Edge bending is positive opposite the direction of rotation.
2. The blade 1 flap and edge bending gages are wired backwards so the slopes have opposite signs of those of the other blades. However, the measurement is in the same orientation for all three blades.
3. The gage specifications listed above correspond to the gages used during Phase IV. The gages used during Phase III were similar, but they were glued to the shaft rather than welded.

Calibration Procedures

Application of known loads - (A1)

A custom jig was used for strain gage calibrations in order to isolate load conditions to one direction only (flap or edge). The jig mounts on the blade slightly inboard of the attachment of the tip block. A cord is attached to the jig, and run over a pulley to the ground where weights are applied. One person in the man-lift mounts the jig on the blade and positions the man-lift so that the pulley is level and square with the cord attachment to the jig. Another person applies the weights in 20 lb increments from 0 to 100 lb. A third person operates the computer to collect samples at each load condition producing new slope values.

Determination of the offset was done differently between Phases III and IV. Essentially, the root flap and edge offsets were determined by placing each blade in a position where the respective load is zero. The offsets for the low-speed shaft gages were determined by recording cyclic bending moments and torque. The average over one complete rotation was equivalent to the offset under zero load.

The slope and offset values were inserted in a temporary header file called *strains.hdr*. This file is read during the *buildhdr.bat* process, and the values are placed in the *master.hdr* file.

Slope coefficient calibration:

1. The man-lift person notifies ground people which blade and which direction (flap or edge) will be calibrated first. The computer person selects the appropriate channel(s) in *vbl.lst* to place at the top of the file. The number of channels to be collected is specified in the first line with NV (number of variables), and the PCM stream on which the channels are contained is selected in *gencal.cap*. All of the strain gages are on PCM stream 2 except the yaw moment strain gages (NAYM) which are on PCM stream 3. During Phase III, the blade strain gages were included with the blade 3 root gages. The low-speed shaft X-X bending channel (LSSXXB) is included with the blade 3 flap bending channel (B3RFB). It is assumed that the low-speed shaft Y-Y bending channel (LSSYYB) has the same slope as bending about the X-X axis. The yaw moment channel (NAYM) is calibrated separately because it is on a different PCM stream than the other strain gages. The low speed shaft torque channel (LSSTQ) is included with each of the three edge bending channels (B1REB, B2REB, B3REB).
2. The *gencal.exe* program is run while the weights are applied from 0 to 100 lb in 20 lb increments with 3 repetitions at each level. *Gencal.exe* is run again while the weights are removed. The recorded weight and count values are stored in the **.cao* input files. A few seconds between application of the weight and collection of data allows any vibrations of the turbine to damp. This is done for both flap and edge directions for each of the three blades to calibrate blade strain gages, low speed shaft X-X bending gages, low speed shaft torque, and yaw moment strain gages. For Phase IV calibrations the blades were loaded in both positive and negative bending conditions.
3. Compute moments in Nm using the following formula:
$$M = \left(\frac{w * \left(R * 39.37 \frac{in}{m} - r \right)}{12 \frac{in}{ft}} \right) 1.35582 \frac{Nm}{ft \cdot lb}$$
where M = Bending moment (Nm), w = weight applied (lb), R = blade radius (5.023 m), and r = radial distance to strain gage (17 in). Plot each curve in Excel, and perform a linear curve fit to determine the slope. Enter the slope values in the temporary header file, *strains.hdr*.

Offset coefficient calibration (Phase III):

1. The man-lift person positions each blade at 90° azimuth angle, and the computer person selects the corresponding root flap bending channel (B1RFB, B2RFB, B3RFB) in the *gencal.exe* input file.

2. The *gencal.exe* program is run with the operator collecting samples. At this location of the rotational cycle, the blade should not be loaded in the flap bending direction (0 Nm) so the count value is used as a single point in determining the offset.
3. The same process is repeated for the root edge bending gages, but each blade is positioned at 180° which corresponds to 0 Nm edge bending moment.
4. Releasing the rotor brake removed any low-speed shaft torque load. The offset was determined by sampling the low-speed shaft torque (LSSTQ) channel. Assuming that the torque measurement is not dependent on the azimuthal position, this method would provide a reasonable offset. This assumption was later determined to be invalid, and a torque correction was created using Phase IV data (Tcorrected = 0.97*Tmeasured - 196.43). This calibration was improved for Phase IV by accounting for the cyclic nature of the torque channel.
5. In order to determine the offset for the low-speed shaft bending channels, the turbine was powered to 72 rpm. The power was shut off, and the rotor slowed to a stop. While the rotor was slowing, the low-speed shaft X-X and Y-Y bending channels (LSSXXB, LSSYYB) were recorded. The average provided the offset at zero load.

Offset coefficient calibration (Phase IV)

1. All of the strain gages, except yaw moment, were listed in a **.cao* file for input to *gencal.exe*. The instrumented blade was positioned at 30° increments over one complete rotational cycle. Three samples were obtained at each position.
2. The offset for flap bending channels was determined by averaging the count value of each blade at 90° and at 270° where the flap load is 0 Nm. This number may be compared with the value obtained by averaging the loads at 0° and at 180° where the average load should be 0 Nm.
3. A similar procedure provided the offset values of the edge bending channels. The average load at 0° and at 180° provided the zero offset while a comparison of the average load at 90° and 270° indicated if the procedure worked properly.
4. The low-speed shaft bending for both X-X and Y-Y axes along with the low speed shaft torque averaged to zero over the complete rotational cycle. This average count value was used to determine the offset.
5. The yaw moment offset was determined by recording the count value when the yaw brake was released in zero wind conditions.
6. The count values obtained under zero-load conditions for each channel were entered in *strains.hdr*.

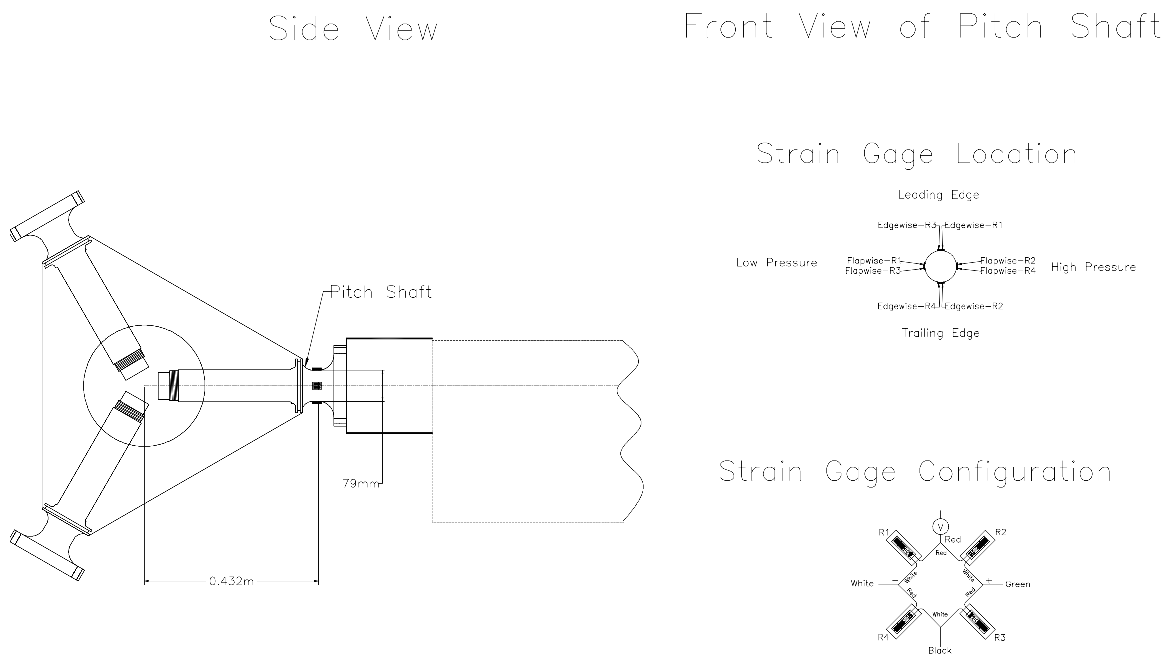
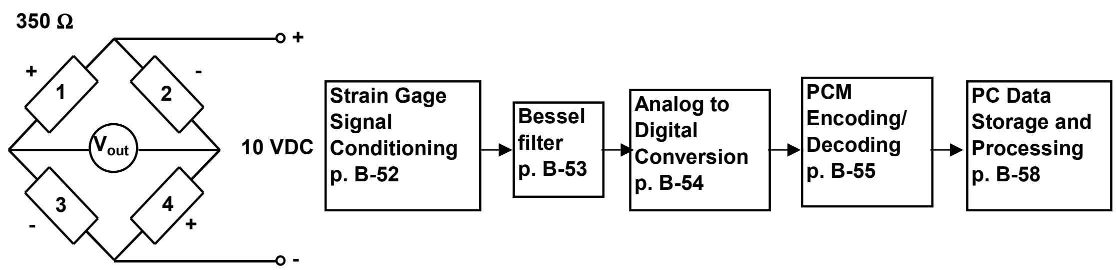


Figure B.6. Root bending strain gage configuration.

Strain Gages (Blade)

Channel	ID Code	Description
215	B325FB	Blade 3 25% flap bending moment (Phase III)
217	B325EB	Blade 3 25% edge bending moment (Phase III)
219	B360FB	Blade 3 60% flap bending moment (Phase III)
221	B360EB	Blade 3 60% edge bending moment (Phase III)

Location	Blade 3, 25% span and 60% span
Measurement type and units	Bending moment, Nm
Excitation	10 Vdc
Range	
Resolution	
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc.



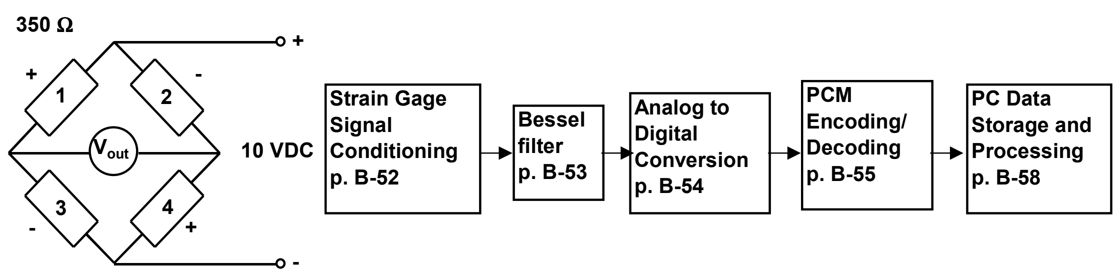
Note:
1. Flap bending is positive in downwind direction; Edge bending is positive in direction of rotation.
2. These strain gages were applied with epoxy within the skin of the blade during manufacturing.

Calibration Procedures (See p. B-21)

Strain Gages (Low-speed Shaft)

Channel	ID Code	Description
237	LSSXXB	X-X low-speed shaft bending moment
239	LSSYYB	Y-Y low-speed shaft bending moment
241	LSSTQ	Low-speed shaft torque

Location	Low speed shaft
Measurement type and units	Bending moment, Nm; torque, Nm
Excitation	10 Vdc
Range	± 50,000 με
Resolution	10,000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: CEA-06-250UW-350 (LSS bending) CEA-06-250US-350 (LSS torque)



Calibration Procedures (See p. B-21)

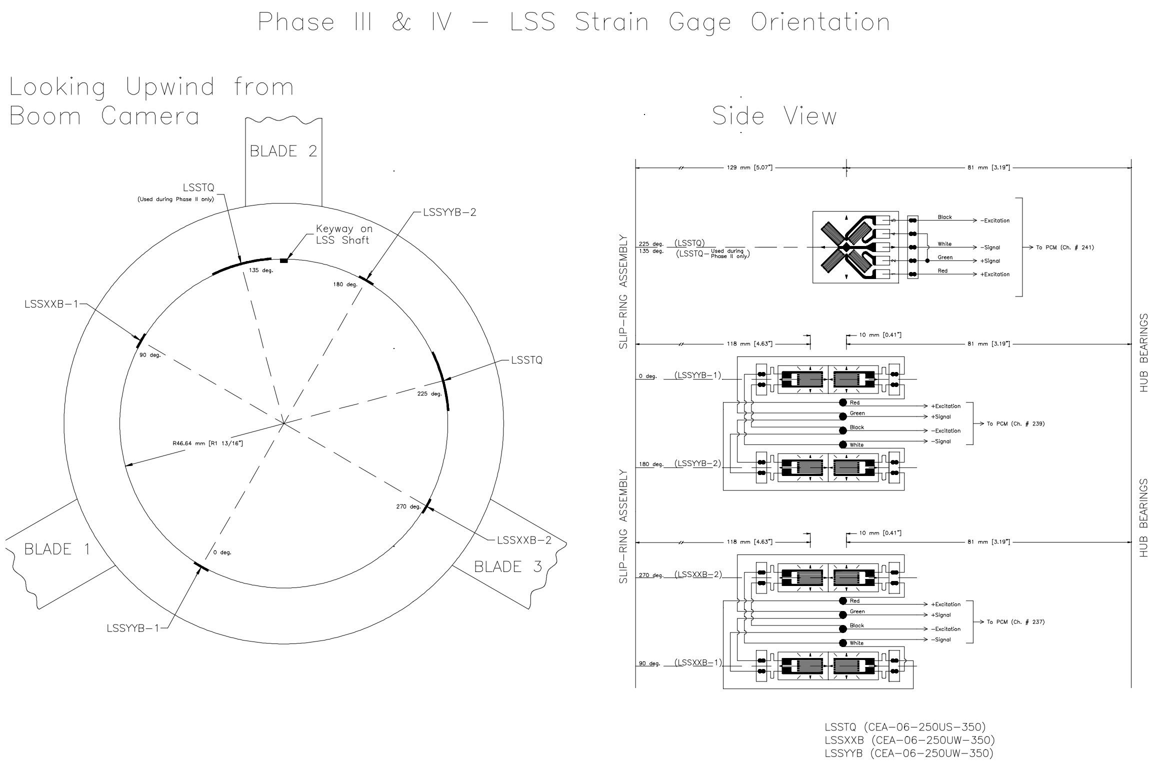


Figure B.7. Low-speed shaft strain gage configuration.

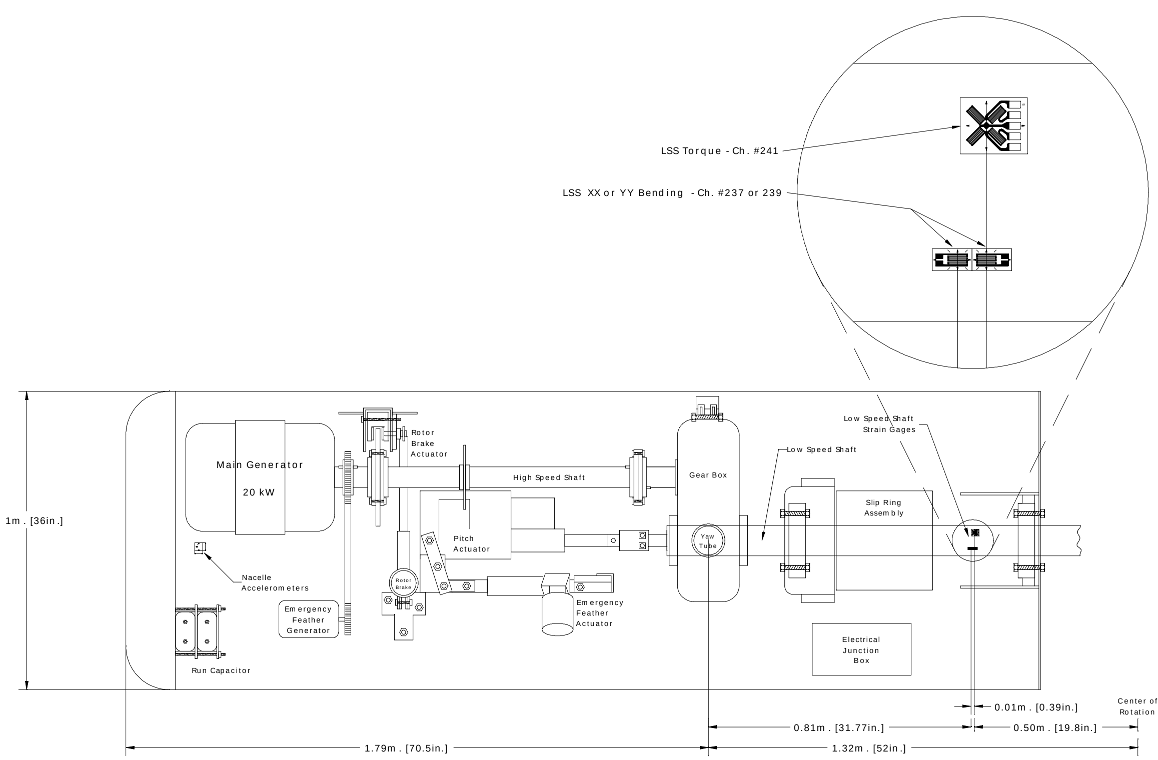
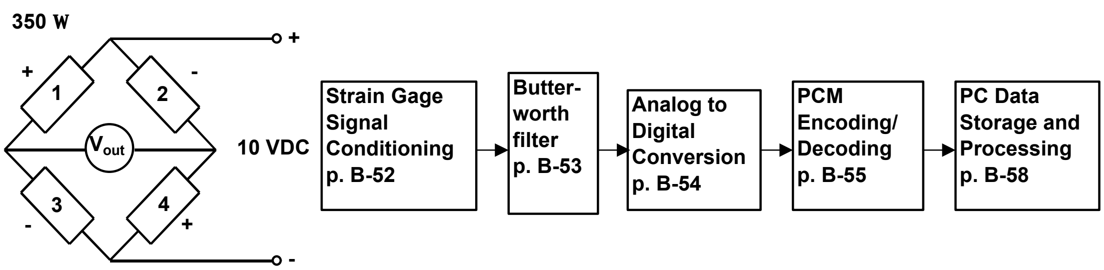


Figure B.8. Low-speed shaft strain gage location within nacelle.

Channel	ID Code	Description
342	NAYM	Nacelle yaw moment

Location	Arms of yaw brake mechanism
Measurement type and units	Bending moment, Nm
Excitation	10 Vdc
Range	
Resolution	
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model:



Calibration Procedures (See p. B-21)

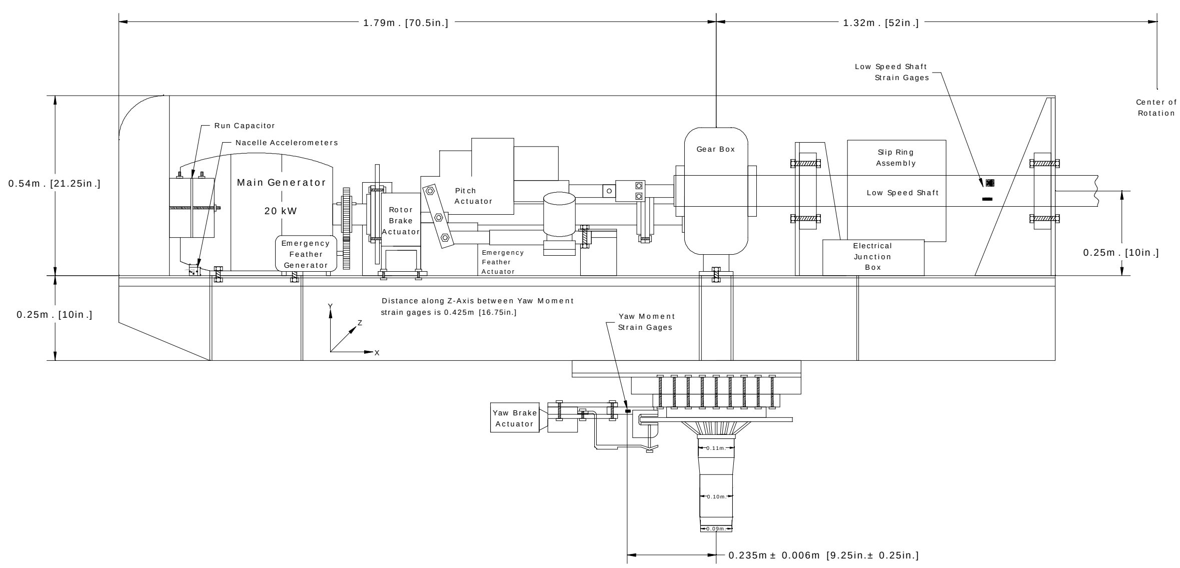
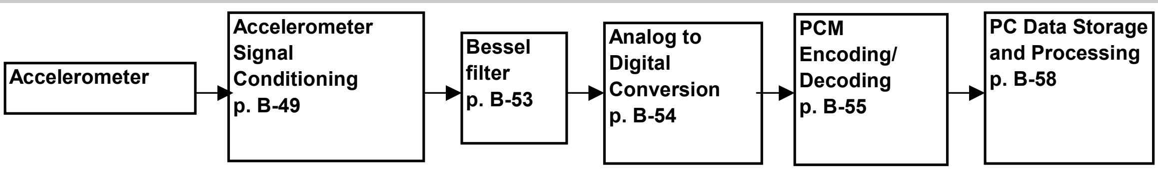


Figure B.9. Yaw moment strain gage configuration.

Accelerometers

Channel	ID Code	Description
201	B1ACFL	Blade 1 tip accelerometer – flap
203	B1ACED	Blade 1 tip accelerometer – edge
205	B2ACFL	Blade 2 tip accelerometer – flap
207	B2ACED	Blade 2 tip accelerometer – edge
209	B3ACFL	Blade 3 tip accelerometer – flap
211	B3ACED	Blade 3 tip accelerometer – edge
336	NAACYW	Nacelle accelerometer – yaw
338	NAACFA	Nacelle accelerometer - fore-aft sway
340	NAACPI	Nacelle accelerometer – pitch

Location	Blade tip, inside tip block; Nacelle bedplate near generator
Measurement type and units	linear acceleration, g's
Excitation	15 Vdc
Range	±10 g = ±2 V
Sensitivity	200 mV / g
Calibration method	Manufacturer specifications (M8) and electronics path calibration (E1)
Sensor description	Variable capacitance accelerometer Endevco Corporation Model: 7290A-10



Calibration Procedure

Manufacturer specifications - (M8)

1. A calibration was performed by Endevco Corporation before installation of the accelerometers.
2. Enter the sensitivity as recorded by Endevco and the offset (0 g) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the accelerometer channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and insure that the correct PCM stream is specified in *gencal.cap* (PCM stream 2 for blade accelerometers and PCM stream 3 for nacelle accelerometers). Because the nacelle accelerometers and the blade tip accelerometers are on different PCM streams, they must be separated into two **.cao* files.

2. Connect the precision voltage generator to the accelerometer output prior to the signal conditioners.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from –0.9 to 0.9 V in 0.2 V increments for nacelle accelerometers (-0.8 to 0.8 in 0.2 V increments for blade accelerometers) with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer provided slope and offset during the *buildhdr.bat* process to obtain units of engineering unit/count and counts respectively.

Calibration frequency

The accelerometers were calibrated upon replacement of damaged accelerometers. An electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.

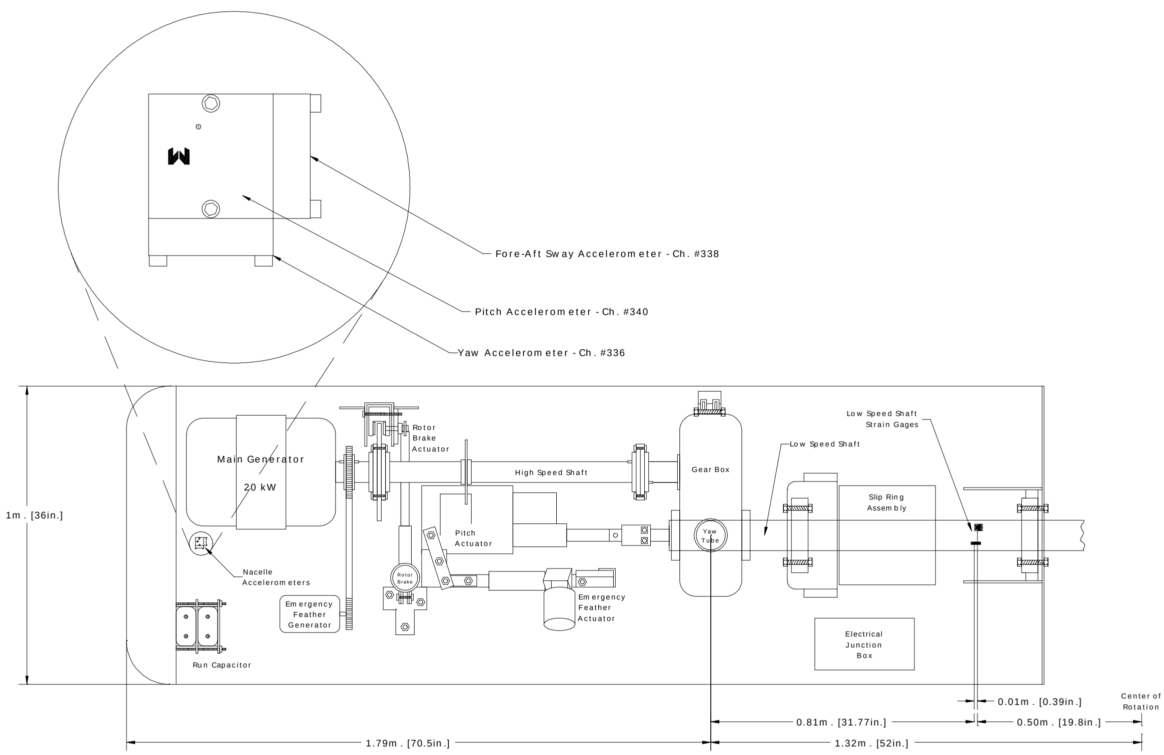


Figure B.10. Nacelle accelerometer configuration.

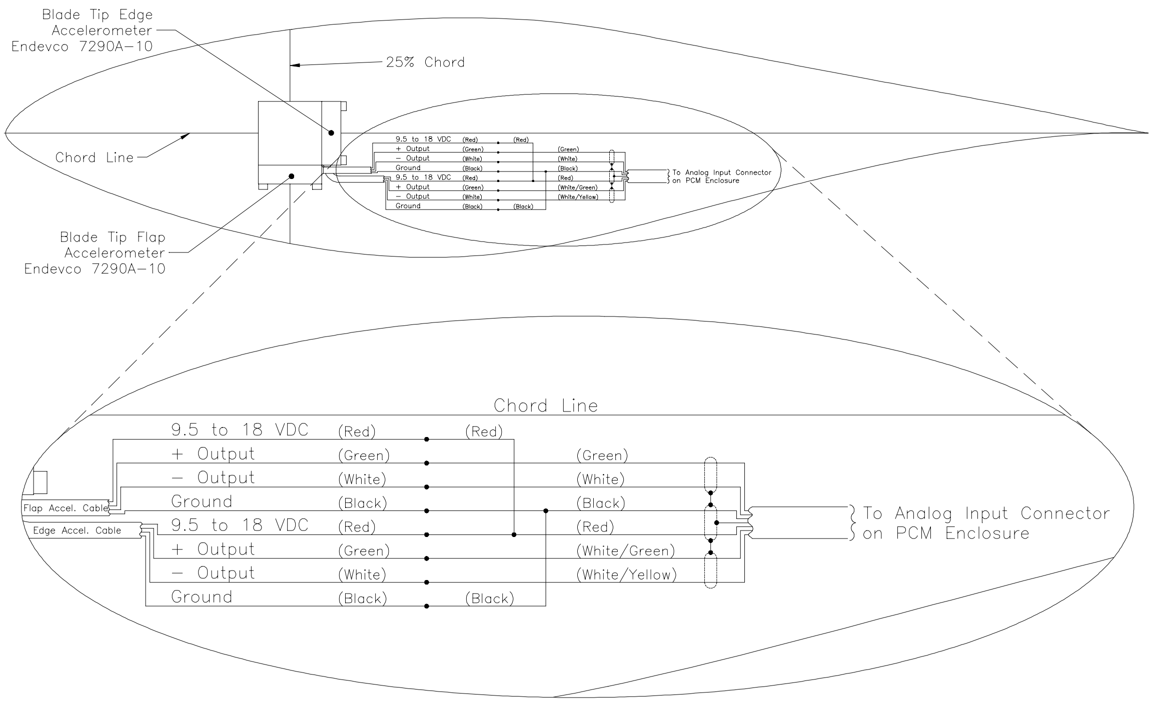
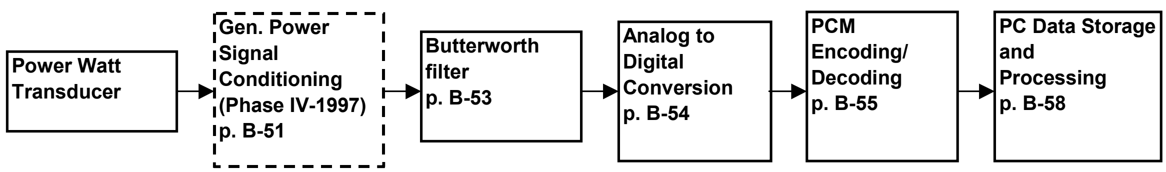


Figure B.11. Blade tip accelerometer configuration.

Power

Channel	ID Code	Description
332	GENPOW	Generator power

Location	Power handling cabinet inside data shed
Measurement type and units	Electrical power, kW
Range	-40 kW to 40 kW = -5V to 5V
Resolution	8 kW/V
Calibration method	Manufacturer specifications (M7) and electronic path calibration (E1)
Sensor description	AC Watt Transducer 3 phase, 3 wire 50/60 Hz Ohio Semitronics, Inc. Model: PC5-63C (DOE#: 00502C)



Calibration Procedure

Manufacturer specifications - (M7)

1. A calibration was performed by NREL Calibration Laboratory before installation of the power Watt transducer.
2. Enter the slope (8 kW/V) and the offset (0 kW) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the power channel is listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and insure that the correct PCM stream is specified in *gencal.cap* (PCM stream 3).
2. Connect the precision voltage generator to the power transducer output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from –4.5 to 4.5 V in 1 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer provided slope and offset during the *buildhdr.bat* process to obtain units of engineering unit/count and counts respectively.

Calibration frequency

The transducer was calibrated in the laboratory prior to Phase III and Phase IV. The electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.